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SOMETHING TO TALK ABOUT: INTERACTION AS DESCRIPTIVE SCHEMA

by

Isaac Lawrence Record

A Thesis Submitted in Partial Fulfillment
of the Requirements for a Degree with Honors
(Electrical and Computer Engineering
with a Minor in Philosophy)

The Honors College

University of Maine

May 2003

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Abstract

A “conceptual schema” is a model or pattern of ideas imposed on reality or experience. A “descriptive schema” is a conceptual schema used to communicate. Because we use these schemas very frequently, a large amount of our knowledge comes to resemble the patterns implicit in them. Because the received descriptive schema is a linear reductionist model of the world, it is unreflective of the emergent features of interaction. I will introduce and develop a new descriptive schema based on these emergent properties of interaction rather than on the reductive properties of individual entities. I will show how this new schema fills in the descriptive gap left by the current schema. Finally, I will speculate about the implications this new schema has for understanding ourselves and the universe in which we live.

Introduction

This paper has four parts. In Part I, I define a “conceptual schema” as a model or pattern of ideas that humans impose on reality or experience. A “descriptive schema” is a shared conceptual schema—that is, a conceptual schema used for communicating. In developing a theory of descriptive schemas, I recount some of the epistemic limitations that pertain to the correspondence between experience and reality. In particular, a psychological effect known as the perseverance effect implies that interpretation of descriptive schemas naturally tends toward realism. To successfully communicate what we know about reality, then, an isomorphism must exist between the elements of descriptive schemas and the elements of reality.

In Part II, I trace the evolution of the received descriptive schema from the animist descriptive schema of the early Greeks to the technologic descriptive schema of the present. The foundation of the technologic schema is the idea that properties of systems are linearly reducible to properties of the singular component objects or relations among those objects. However, because many natural systems are nonlinear, the technologic schema critically fails to reflect many of the essential elements of reality.

In Part III, I propose a generalization of the technologic schema: an interaction schema based on the emergent behaviors of physical interaction. My argument is that we can view the whole universe as being composed of systems whose complexities range from order to chaos. An investigation of the properties of cellular automaton systems reveals that this spectrum divides neatly into four classes of interaction. The technologic schema critically ignores the class I call dynamically stable. Dynamically stable systems can exhibit behaviors impossible for their interactants. That is, behaviors of the ensemble emerge from the structured interactions of constituent entities.

Finally, I suggest that reality is composed of a hierarchy of interactions. This and other implications of the interaction descriptive schema are the subject of Part IV.

For John Lind, who taught me to wonder.

In theory, there is no difference between theory and practice. But in practice there is.

—Yogi Berra

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Part I. Descriptive Schemas

Every descriptive schema contains a fundamental assumption about the world and results in a fundamental method of interacting with the world. Part II is about the assumption and method of the descriptive schema with which all Westerners are familiar. I have termed this descriptive schema “technologic” to encapsulate the assumption that physical things are **reducible**¹ and are therefore both predictable and controllable. We will then see that the initial assumption is flawed and that, therefore, so is the method of interaction. In Parts III and IV, I propose that we view the universe as a hierarchy of systems and the effects of our actions on each of these levels must be considered. Before we arrive there, however, we must first see what defines a descriptive schema.

The following sections introduce the concept of descriptive schema. I will define descriptive schema and contrast it with related psychological and philosophic concepts, discuss the practical and theoretical limitations on descriptive schemas and human knowledge in general, and explain how descriptive schemas develop and change.

¹ As I use the term here, a system is reducible when the whole can be understood as nothing more or less than the sum of its constituent parts.

Section 1. Definition

In psychology and philosophy, a ***conceptual schema*** is a mental structure used to organize our experiences of the world. By 'mental structure,' I mean something more than, say, a mapping of brain neurons, because knowing the brain structure is—or appears to be—insufficient for knowing the mental structure it instantiates, though mental processes undoubtedly emerge from brain processes in some fashion. At an even higher level of abstraction, concepts comprise relatively stable mental processes. A conceptual schema is a relatively stable collection of concepts. The process of learning a conceptual schema is in some ways similar to the process of learning a language. For example, humans have an innate capacity to create conceptual schemas, but some of the details are environmentally (rather than genetically) determined. That is, just as any healthy baby can learn any human language, any healthy baby can learn any human conceptual schema. Another similarity to language is that conceptual schemas are not consciously constructed conventions (as are, for example, the rules of handball). A ***descriptive schema*** is simply a conceptual schema used for communicating information rather than just organizing it. Because of this, descriptive schemas make significant use of language that other conceptual schemas might not.

In psychology, schemas² are the “mental structures people use to organize their knowledge about the world by themes or subjects; schemas powerfully affect what information we notice, think about, and remember” (Aronson 7). Stereotypes are a simple type of conceptual schema. For example, similar experiences with a few individuals lead us to try to group these individuals based on their similarities in appearance and behavior. We assign new individuals to classes based on appearance

² The term 'schema' without the appellation 'descriptive' or 'conceptual' refers to schemas of both types.

and then formulate expectations about their behaviors based on those associated with that class. Conceptual schemas are a necessary part of human experience; in the course of a normal day, we encounter large amounts of data but have the cognitive capacity to interpret this data in only a small fraction of possible ways. Conceptual schemas comprise the set ways we use to analyze data. The intent is to ignore inconsequential details but preserve essential features in a simplified representation of some worldly artifact.³ Thus, 'rainstorm' leaves out details like wind speed and the size of raindrops, but retains the essential information—steady liquid precipitation. But which features are inconsequential and which essential? Basically, people assume that whatever was important in the past will be important in the future: whatever features were essential to making a successful judgment⁴ before will continue to be the essential features, and whatever features were inconsequential or misleading before can henceforth be safely ignored. It is normally only when these simplistic operations fail that people consciously analyze the artifact in question.

Again, the descriptive schema is essentially a variation on the common psychological concept of a conceptual schema. It might well seem that descriptive schemas simply compose the set of shared conceptual schemas; that there is nothing fundamentally new here (which might suggest that its addition to the language of psychology or philosophy is redundant or misleading). However, the usage of descriptive schemas in communication is enough to set it apart from conceptual schemas.

For an individual, the cognitive role of a descriptive schema is essentially no different from that of a conceptual schema. Nevertheless, everyone who learns a

³ Such as an object, person, or system (e.g. "chair," "Isaac," or "the weather").

⁴ What constitutes a "successful judgment" is whatever seems successful *to the individual*; for schemas, this determination may involve both conscious and unconscious processes.

particular descriptive schema understands it conventionally. That is, what sentences mean is (essentially) consistent amongst the entire group that shares the descriptive schema. Moreover, it is in this setting that the essential role of the descriptive schema arises; it is not primarily an internalized mental structure used to *organize* the world, but an internalized mental structure used to *talk about* the world (though of course the organizing of the world comes with the package, for better or worse). Put another way, descriptive schemas are a venue for translating ideas into a language like English without having to spell out all the details. As such, the broader in scope a descriptive schema is, the greater utility it has. This characteristic breadth is part of what differentiates descriptive schemas from other schemas. The utility of many *conceptual* schemas arises from their narrow focus.

Because we use descriptive schemas to communicate, they are also more explicitly bound to language than conceptual schemas (which might also encode emotional or sensory content), and this basis in language makes them more rigid than conceptual schemas need be. To paraphrase George Carlin, we have ideas, and ideas are malleable. Then we assign a schema to that idea, and we are stuck with that schema for that idea. Effectively, the schema binds the idea so that there is essentially only one way to interpret the data. It is possible to shift this interpretation through conscious effort, but doing so works against the role of descriptive schema as a touchstone in communication. This constancy of interpretation is both the advantage and disadvantage to schemas—they save time, but do not admit data that do not fit its patterns. In addition, there are limitations on what exactly can be a descriptive schema. Some of these limitations are practical, but others are deeper—based on the

epistemological limitations of human knowledge and theoretical limitations of computation.

Section 2. Limitations of Descriptive Schemas

Though particular descriptive schemas have advantages and disadvantages particular to their specific formulation, the whole class of mental structures that qualify as descriptive schemas share limitations which fall into two broad categories: practical and theoretical. Practical limitations of descriptive schemas are those limitations that arise from the use of descriptive schemas in describing the world. Theoretical limitations, by contrast, are those epistemological limitations on human knowledge that affect all manners of describing the world—including, of course, descriptive schemas. The next two subsections deal with these two subjects in turn.

Subsection i. Practical Limitations of Descriptive Schemas

Any time we speak of the world of experience in terms of some simplified model, there is an implicit assumption that the model resembles—in some respect—the reality we intend it to describe. However, it is the responsibility of the person choosing the schema to be sure that this resemblance is there. Otherwise, we cannot be sure, for example, that theories are about what they say they are about. There are a few examples where this discrepancy between model and reality are explicit. In the preface to *De Revolutionibus* is a claim by Osteander that the mathematical model described therein is simply that—a *mathematical* model, not at all about how planets actually move (Copernicus 3). Even if politically motivated in this instance, the denial of correspondence between model and reality has lately become rather common. For example, in quantum mechanics, both matrix and wave equations yield apparently accurate results, yet the components of one do not appear in any sense to resemble those of the other. This gap between mechanics and interpretation extends into everyday subjects as well. Henri Poincare is famous for observing that we force our geometry on the world as a matter of habit, where any of several interpretations could as easily obtain (Poincare 104).⁵ However, model-reality correspondence is not the only challenge descriptive schemas face. For even if there is some amount of correspondence between the elements of a model and the elements of reality, the abstract (simplifying) nature of schemas can lead to problems.

⁵ Euclid's geometry, which corresponds to common-sense geometry, is composed of five axioms. The first four straightforwardly define points, lines, circles, and right angles. The fifth is not quite so graceful: "given any straight line and a point not on it, there exists exactly one straight line that passes through that point and never intersects the first line." Denying the fifth postulate in various ways leads to new geometries. For example, denying that any such line exists results in elliptical geometry, in which all lines intersect one another, as all lines of longitude intersect at the north pole. Incidentally, elliptical geometry seems to better describe relativistic space than does Euclidean (Hofstadter 90).

We all know that it is dangerous to take an analogy too far. When Da Vinci tells us to “observe the motion of the surface of the water, how it resembles that of hair, which has two movements—one depends on the weight of the hair, the other on the direction of the curls; thus the water forms whirling eddies, one part following the impetus of the chief current, and the other following the incidental motion and return flow” (Da Vinci 25), he does not intend for us to believe that hair and water are equivalent. The analogy ends at the comparison of the shapes they take. Drawing further conclusions based on, say, differences in hair color, would almost certainly be irrelevant to the discussion of water. The same sort of limitation usually exists for descriptive schemas. There is a point beyond which the analogy cannot go—a point where the parts left out of the abstraction become important. For example, the abstraction of water as a continuous fluid fails at microscopic scales where the features of the H₂O molecule come to have great enough influence over fluid dynamics that ignoring this discreteness becomes implausible—as when water freezes into ice.

Descriptive schemas are also limited in the same way as the conceptual schemas widely discussed in psychology. People tend to have very few truly general descriptive schemas at their disposal,⁶ and there is a psychological necessity to believe that they work—partly because we use them so often. Oftentimes, people will distort data to fit with their schema or ignore data inconsistent with their schema rather than altering their schema to admit the troublesome data—so it is that sports fans become convinced that referees are out to get their team. Indeed, people maintain their schemas long after they have been discredited (this helps explain, for example, the persistence of racism). Psychologists call this the ***perseverance effect*** (Alston 72-75). Schemas can

⁶ In following Parts, we will see several schemas that are familiar to us, but it is likely that we are seeing each of them in terms of one active schema rather than ducking inside of each one.

act as self-reinforcing feedback loops: the more often one is right, the more often people use it. An insidious consequence of the perseverance effect is that the more often people use a schema, the more likely they are to distort reality to fit within the schema, and the more likely the schema is to appear right. In this way, schemas resemble self-fulfilling prophecy—the whole body of knowledge comes to resemble the schema simply because people have the expectation that the schema is accurate. This expectation stems from a far more basic psychological necessity—the assumption of regularity built into our implicit belief in induction.

Hume describes the problem of induction as an imposition of our psychological necessities on the world (in Cahn 644). The problem is that an inductive conclusion (such as a schema-based prediction) extends logically beyond the content of its supportive premises. The justification for this extension is a claim of regularity. The justification for this claim of regularity (that past regularity supports future regularity) is itself inductive. The only justification for induction is itself inductive—a circular, and therefore inconclusive, argument. This and other psychological necessities fall into a separate category of limitations for descriptive schemas—the theoretical limitations that apply to all methods of human knowledge about the world.

Subsection ii. Theoretical Limitations of Descriptive Schemas

Humans have finite cognitive abilities, finite senses, and finite memories. This is part of the reason we use shortcut methods such as descriptive schemas to sift through data. Even without using shortcut methods, however, the finite nature of human beings leads to limitations on what we can know about the world, and some of these limitations are particularly important in the context of descriptive schemas. Furthermore, there is a potential limitation to knowledge that is not rooted in the finite nature of human beings but on computation in general. The following section discusses these in turn.

Perhaps the most famous image in all of Western thought is that of Plato's Cave. The image is striking: humans are pictured as chained so that they can see only shadows cast by firelight onto the walls of the cave. Essentially everything humans experience is artificial: the images they see are distorted shadows of reality and the light of the cave is the artificial light of socialization (and this is probably where descriptive schema fits best into the cave metaphor). This image presents a very grim picture of human knowledge (essentially, that all observational 'knowledge' is a distorted illusion), but by no means is it the grimmest possible picture, for at least Plato admits the possibility that both the world and human minds do exist—points about which some philosophers are skeptical. Nevertheless, we will stipulate that there are indeed minds and a material world, and instead focus our attention on the correspondence between the perceived world and the real one. That is, the discussion will take place in the context of the realist-antirealist debate about truth.

Realism, as I will use the term here, is the semantic and metaphysical doctrine that sentences are truth-evaluable. For example, "snow is white" is true if and only if snow is white, which entails that if "snow is white" is true, then there is a thing *snow* that has

the quality *white*. Antirealism, by contrast, encompasses a family of objections that commonly assert that realist truth is the wrong concept to apply to the discussion. For example, and in particular, instrumentalism claims that sentences should not be evaluated based on correspondence with the world; rather, they should be evaluated on their utility as tools for predictively controlling the world.

Humans generally perceive the world as a collection of objects. Much of the realist-antirealist debate revolves around the cognition of objects—that is, the process of dividing the world into more basic bits. By what principle, ask antirealists, do realists divide objects? How can they know that this principle is universal, objective, or somehow corresponding with actual divisions in the world? In other words, what exists in the world, and what exists as an artifact of our perception of the world? This is a longstanding debate, and it is perhaps useful to briefly review the relevant parts of its history.

Locke separates qualities of the world into two classes: primary qualities, which cannot be separated from the object, like figure, extension, and number; and secondary qualities, combinations of primary qualities which cause various sensations not resembling their causes (like color and sound) (in Cahn 502). David Hume focuses his debate somewhat more internally, but also ends up with two classes: impressions, which are much like Locke's secondary qualities in that they are externally caused (though Hume emphasizes that impressions may be independent of any correspondence to actual externals); and ideas, which are less lively remnants of impressions (in Cahn 634). Kant follows Hume, but clarifies the terminology in the following way: appearances are available to us, but they must conform to our sensitive *and* cognitive faculties. Things in themselves are simply unavailable to us. What this means for

schemas is that, at best, schemas refer to the appearance of the world, rather than the world itself. Because a descriptive schema is primarily a language-based schema, it is necessary to discuss how language reflects the world.

To reframe the original question of object correspondence in terms of language correspondence, Cortens says, "in a sense, a language can be said to describe the world as it is in itself only if there is an appropriate isomorphism between it and the world" (55). In such a view, "'X is a chair,' [if true, is supposed to] mirror the structure of reality just as [it stands]. Although such sentences are normally used to convey truths, they do so in an *unperspicuous* fashion." For Cortens, the modern-day perspicuous version would involve 'simples arranged chairwise,' where 'simples' are, say, elementary particles (55)⁷. That is, language is a shortcut. When we say 'X is a chair,' we really mean that 'X is a collection of simples arranged chairwise.' The only reason we do not say it that way to begin with is that language *automatically conveys this format schematically*. That is, for Cortens, it is simply a feature of language to provide shorthand notations for objects to which we commonly refer. But "what objective fact about the world makes us [prefer one type] over the infinitely many types of objects a particular [entity] can compose?" (Lynch 63) Why, in other words, do we say 'simples arranged chairwise' instead of, say, 'simples arranged kindlingwise'?

According to Sosa, our conceptual scheme implicitly recognizes some 'arrangements of simples' while ignoring others based on our needs or interests, rather than on the subject matter itself. An object that is a "chair" in one context is quite reasonably "kindling wood" in another. Lynch suggests three ways to deal with this introduction of subjectivity:

⁷ Another possible "perspicuous version" might involve the substances earth, air, fire, and water.

- 1.) We can recognize all possible matter/form combinations and know that “any attempt to state which objects exist is bound to capture only part of the truth” because the list of all possible combinations is infinite.
- 2.) We can choose the eliminativist approach, and claim that only basic elements exist (for example, particles such as quarks and leptons) and all object formation is in our heads—a mere convenience (similar to Cortens approach above).
- 3.) Or we can choose the relativist approach, and claim instead that the existence of objects is contingent upon (or relative to) some conceptual scheme.

—Adapted from 63

It might at first seem that, because we are only discussing descriptive schemas, we need not accept that these choices have *real* metaphysical implications, only *apparent* ones. After all, we use descriptive schemas loosely, and this loose use is acceptable as common practice because it is merely a convenience. This might seem to be the easy way out, but it ignores the perseverance effect. As we shall see, psychology necessitates actual belief in descriptive schemas, so we must stipulate the metaphysical realism of its components.

“The world we care about and want to predict and control and understand is the world of experience, not the world of things in themselves” (Kant in Glymour 108). The world of experience is the world we think about, live in, and talk about. Because descriptive schemas inform all three of these activities, the world of experience is the world of descriptive schema. Descriptive schemas are instrumental, but that does not mean that any who use them must be metaphysical instrumentalists, for descriptive schemas do not make metaphysical claims of this kind. Indeed, if a descriptive schema does make a metaphysical claim, it will be a realist claim based on the psychological

tendencies of humans to believe that descriptive schemas really reflect the world.⁸ In other words, the perseverance effect forces us to take the claims of our descriptive schemas more seriously—to accept that components of the real world do correspond with the components described by a descriptive schema, rather than that they are incomplete descriptions or merely conveniences. Because we use descriptive schemas voluntarily⁹ and because we create them based on our needs or interests (of this, more in the next section) we must accept that the very existence of the components described therein are contingent upon the choice of that schema to describe reality. The psychological perseverance effect, then, causes us to choose the third option—whether we would really like to or not.

Because of the relativism this choice implies, it becomes extremely important that a schema actually correspond as closely as possible with reality. Because of the perseverance effect, descriptive schemas walk a hard line: they are a voluntary convenience, but when we apply them, we have to believe in their reality—for schemas greatly affect what we know about the world. The only way to ‘save reality’ from its contingency on our whim is to make sure that the whole of the schema really corresponds to the whole of reality. With conscious attention, this should be possible, as long as there is some correspondence between experience and reality.

Even if future scientific discoveries or technological advances obviate the limitations discussed above, a more fundamental limitation to computational processes in general would still obtain. One version of the problem afflicts the very concept of truth. Termed

⁸ Through constant conscious attention, of course, we can overcome or hide our realist tendencies—as when we learn to avoid flinching in certain childhood games. But without such attentions, we tend to slide easily back into believing that the world we perceive is the real world.

⁹ In the context of cognition, that is. Avoiding a descriptive schema while communicating requires a high degree of attention to detail.

the Epimenides or Liar's Paradox, it takes the form of a paradoxical, self-referential statement such as the English sentence "This statement is a lie." The problem is that, if true, the statement must be false. But if false, the statement must be true. As we shall see, this semantic paradox has a syntactic counterpart that apparently afflicts all formal systems of sufficient power.¹⁰

In his attempt to rigorously formalize mathematics, Russell came upon a problem with the formalization of set theory. The problem is that, at least in the usual sense of the term, sets can contain themselves. For example, the set containing self-membered sets contains itself. Most of the time, this is unproblematic. But if **S** is the set of all sets that do not contain themselves, does **S** contain itself, or not? If **S** does *not* contain itself, then by definition it *must* belong to **S**. But if **S** belongs to **S**, then by definition **S** *cannot* belong to **S**. For years after Russell's discovery, mathematicians attempted to discover a formalization of mathematics that had the same power but which was not vulnerable to the same paradox. Then Gödel published his Incompleteness Theorem, which shows that no consistent axiom system of arithmetic can be complete—that is, the truth of some statements within the system cannot be proved (or disproved) within the system. Without going into the details, the Gödel's method was to encode the mathematical equivalent to the self-referential statement "this statement is unprovable." As with the English language version, having an answer would create an inconsistency, and so it is rather fortunate that no answer can be had. Slightly more accessible is Turing's related proof of the insolubility of the Halting Problem, which we discuss in detail below.

¹⁰ For the moment, let us leave undefined what "sufficient power" entails. These examples suggest that the capacity for creating self-referential statements comes along with this power, whatever it may be.

A **decision procedure** is an algorithm, a systematic procedure that yields a yes or no answer to a problem. A decision procedure is **decidable** if it yields a definite answer in finite time. The procedure is **correct** if it yields the right answer. The halting problem asks whether there can be a decidable, correct algorithm that determines for all possible procedures and inputs whether that procedure halts (that is, comes to some concluding state) for that input. Let us assume for the moment that such a decision procedure, call it **H**, exists. Then we can supply **H** with a procedure **P** and input **I** and in finite time **H** will conclude correctly that **P** halts or does not halt for **I**. Formally, we could say that $H(P, I) = \text{TRUE}$ if **P** halts for **I**, and $H(P, I) = \text{FALSE}$ if **P** does not halt for **I**. So, for example, $H(H, P(I)) = \text{TRUE}$ for all **P** and **I** by our assumption that **H** exists.

Now let us construct a procedure **K** that takes as input a procedure **P** and input **I** and which loops forever if **P(I)** halts, and halts if **P(I)** does not halt. That is,

```

K(P,I) {
    IF  $H(P,I)=\text{TRUE}$  THEN DO NOT HALT
    OTHERWISE HALT
}

```

Since **K** is a program, it may be run on itself, so that if $H(K,K)=\text{TRUE}$ (**K** halts) **K** does not halt. Alternatively, if $H(K,K)=\text{FALSE}$ (**K** does not halt) **K** halts. Both of these cases are contradictory, and so our initial assumption (that **H** exists) is flawed.¹¹ In other words, no decision procedure can be a solution to the halting program, so there is no finite method to determine generally whether a decision procedure is finite. That is, there are questions about decision procedures that are **undecidable**.

The Epimenides paradox is an example of a statement in English whose truth cannot be determined. Any descriptive schema that allows for self-reference, classical negation and the concept of truth and falsity is susceptible to the same limitation. The

¹¹ This solution is a broad paraphrase of a more formal proof given by Alan Turing.

other variations of this problem, including the Halting Problem, demonstrate a limitation held by a certain kind of formal system. Obviously, if descriptive schemas or the systems they describe are of this type, then this same limitation afflicts them. That is, there are questions about them that are undecidable.

We will eventually return to this question, but first, we will discuss how descriptive schemas arise and change.

Section 3. Changing Descriptive Schemas

It is relatively easy for people to change conceptual schemas. Despite the perseverance effect, conscious effort makes it possible to reinterpret or reformulate any conceptual schema. Because descriptive schemas are conceptual schemas, they are just as easy to change on an individual basis. However, because descriptive schemas are *shared* conceptual schemas, changing them becomes a collective effort, rather than an individual one. This makes changing them somewhat more difficult.

Descriptive schemas are most useful when their application becomes second nature. As a result, people maintain only a few descriptive schemas (say, one primary and perhaps a few specialized schemas), because the marginal utility in descriptive power gained by learning additional descriptive schemas is quickly overshadowed by the large investment of time and effort required to learn them.¹² Still, dramatically new descriptive schemas do occasionally arise, perhaps because they better correspond with reality or because they more usefully describe the components of reality.

The way it happens, however, is not at all gradual. Rather, the entire structure of understanding must be replaced all at once, as soon as a certain critical mass of discrepancy between schema and world exists (Glymour 124).¹³ People voluntarily eschew the use of the schema to discuss these discrepancies. When the importance of these discrepancies rises even further, so that a large enough proportion of the information people talk about falls outside the scope of existing schemas, people create a new schema, perhaps by incorporating parts of existing conceptual schemas into the

¹² Though it is not impossible to do so, people normally do not consciously perform a cost-benefit analysis on the time and effort required to pick up a new descriptive schema. Nor do they usually set out to acquire a new descriptive schema. Like learning a first language, people generally acquire a descriptive schema as a part of growing up in a given society.

¹³ The similarity of this idea to Kuhn's theory of scientific revolutions of paradigm is incidental, though for convenience I have adopted similar language.

descriptive schema. In Part II, we will discuss the development and limitations of the modern technologic schema, showing how the major pieces came together over millennia.

Part II: Technologic Schema

In Part I, I defined a descriptive schema as a voluntary, shared abstraction created for the purpose of concise communication of information about the world. The psychological tendency of humans to fit data to their models and ignore incongruities causes entire bodies of knowledge to come to resemble the schemas used to organize them. The perseverance effect causes us to grant reality to the components of descriptive schemas. This, in turn, causes us something of an ontological crisis, since existence becomes contingent on thinking in terms of the descriptive schema, and thinking in terms of the descriptive schema can be motivated by the wish to communicate rather than being motivated by the wish to find a schema that adequately represents the idea. The only way to resolve this crisis is to ensure that descriptive schemas really do closely reflect reality. It is now time to apply these ideas to some real descriptive schemas.

Up until about three thousand years ago, the central descriptive schema in the West was animist. The essential assumption in the animist schema is that all things have a spirit and the natural role of humans is as deferential to nature. The modern descriptive schema is quite different. In its latest iteration, I call the modern descriptive schema “technologic” to encapsulate the essential assumption that the universe is reducible to properties of fundamental objects and the consequent role of humans as masters of nature. In this Part, we shall see just how the former descriptive schema came to be the latter.

Though the primary schema of any culture remains constant for a great majority of the time, over the course of three thousand years, this equilibrium was punctuated by brief periods in which new elements were introduced to the central schema. As of three

hundred years ago, the technologic schema was king, and almost nothing remained of the original animist schema.¹⁴ The modern schema has reigned virtually unchanged over the era of industry and predictive control. Despite its incredible success, there are limitations to the technologic schema, and these limitations have lately become critical. The next several sections deal with these subjects in detail.

¹⁴ Although forms of the animist schema are still in use, particularly in the realm of biological systems.

Section 1: Animism

In the days before written history, much of human knowledge was collected in the form of oral traditions; one example is the Greek mythology with which most of us are, to some degree, still familiar. By modern standards, this mytho-poetic tradition of knowledge is inconsistent and riddled with the supernatural and anthropomorphic description¹⁵ (Lloyd 8, 11-12). What we do not now realize (without study) is that these poetic formulations are not meant to explain the world so much as to describe them in familiar terms or simply find meaning in the world. As such, there is no requirement of consistency, and no call for descriptions to refer to actual mechanisms of nature.

Around 600BC, in Miletus,¹⁶ that begins to change. A thinker named Thales omits mention of the gods in his account of earthquakes, preferring instead a naturalistic explanation. Instead of describing a petulant god, Thales claims that the earth floats upon a great sea, whose occasional waves cause the earth to shake (Lloyd 16).¹⁷ Thales (who claims elsewhere that everything is full of gods) means this description to be a consistent *explanation* of a natural phenomenon, not just a description of occurrences, so it is subject to debate. It is for this reason that it serves as a convenient marker of the beginning of the long tradition of Western philosophy and science, which grew steadily until the days of Aristotle, perhaps the most influential Greek thinker, who captures the essence of the technologic schema in his claim that we understand that which we can make (Cahn 209).

¹⁵ That is to say, they impose human will and motivation on non-human objects or events.

¹⁶ At the time, Miletus was an economic and cultural crossroads of ancient Greece. This probably served to turn the city into a reservoir for information from all over the ancient world. This increase in general knowledge of worldly events probably had as much to do with the rise of explanation as any other factor, for it was only at this time that the body of knowledge could support detailed comparisons between the familiar and the unfamiliar.

¹⁷ This bears a qualitative resemblance to modern theories of plates floating on a "sea" of magma.

Section 2: Foundations of Technologism

Even after Thales (et al) established that human knowledge ought to explain the world rather than simply describe it, and Aristotle (et al) determined that the making of a thing was sufficient for understanding it, there was still much work to be done before the technologic schema was complete. For Aristotle's program was so influential that there was effectively a fifteen hundred year moratorium on observational science—his word and his world were accepted without question.¹⁸ Eventually, this changed. Leonardo Da Vinci figures importantly in (or, at least, gets a lot of credit for) these changes. Da Vinci is famous for his voracious curiosity, prolific note taking, and revolutionary ideas, but Da Vinci still conceived the world primarily in organic terms. "The earth has a vegetative soul... its flesh is the land, its bones are the structures of the rocks... its blood is the pools of water... its breathing and its pulses are the ebb and flow of the sea" (qtd. in Crane 3).

Galileo adds a few more major building blocks to the technological view of the world. He puts into words the concept of universality—first, that natural processes are law-bound, and second that these laws are consistent throughout time and space. He abandons final causes as an explanatory mechanism. In addition, Galileo believes that

this grand book of the universe... cannot be understood unless one first comes to comprehend the language and to read the alphabet in which it is composed. It is written in the language of mathematics and its characters are triangles, circles, and other geometric figures, without which it is humanly impossible to understand a single word of it.

—In Crane 4

Machiavelli famously omits all mention of God in his accounting of the free will of men; instead

¹⁸ There are exceptions to this, but once the Catholic church adopted Aristotle's doctrine, many such doubts were forgotten.

fortune is arbiter of half our actions, but...she leaves the other half...for us to govern. And I liken her to one of these violent rivers which, when they become enraged, flood the plains, ruin the trees and the buildings, lift earth from this part, drop in another; each person flees before them, everyone yields to their impetus without being able to hinder them in any regard. And although they are like this, it is not as if men, when times are quiet, could not provide for them with dikes and dams so that when they rise later, either they do by a canal or their impetus is neither so wonton nor so damaging.

—Machiavelli 98

In case this leaves any doubt as to what Machiavelli believes to be the relationship between man and nature, he reminds his reader that fortune¹⁹ "is a woman; and it is necessary, if one wants to hold her down, to beat her and strike her down" (101).²⁰ Machiavelli's most avid admirer, Sir Francis Bacon, leaves even less to the imagination. The role of mankind is to "conquer nature in action" (21). Bacon even offers up a method of action: the scientific method. Bacon disposes of syllogism, the logically sound deductive method, on the basis that no truly new information can be gotten from deductive logic; in a sense, any conclusion one might reach was already there in the premises, and any fault in the premises necessarily carries to the conclusion. Instead, Bacon supports inductive reasoning with experimental confirmation. He has no doubt that his method will soon make man the absolute master of nature.

¹⁹ For Machiavelli, the two players in worldly events are free will and chance.

²⁰ However distasteful this metaphor is in the modern parlance (and not only because man:woman::humans:nature resembles an SAT question), it leaves no doubt as to Machiavelli's meaning. In fact, we have learned his lesson so well that, were the same thing written today, we might take it to be a comment on men and women, rather than on humans and nature.

Section 3: Predictive Control

In engineering and the applied sciences, it is normal to set up models so that they are linear (and therefore predictable—for what good is a model that is unpredictable?). Linear systems are deterministic (there can be exactly one response for a given input), output is proportional to input, and overall system behavior is exactly the sum of the parts (Stacey 25). In fact, it turns out that linear systems are often described in terms of **attractors**: “trajectories followed by a system converge asymptotically over time. In other words, an attractor is a pattern of behavior into which a system ultimately settles in the absence of outside influences” (Stacey 54). There are three kinds of attractors: stable equilibrium, unstable, and strange.

Stable equilibrium attractors, for example a pendulum in a gravitational field, always resolve to some stable or periodic final state. Unstable attractors tend toward infinity or else exhibit chaotic behavior. These systems normally involve positive feedback, in which small disturbances are amplified to the point that they affect global behavior of the system. Strange attractors fall between these two categories. They normally follow some general pattern, but never quite repeat themselves.

Systems of the first type are predictable and normally controllable as well. Systems of the second type are normally predictable within small regions, but are usually too unstable to be controlled. Systems of the third type can often be predicted in terms of gross behavior, but they cannot be controlled or predicted in detail. Bacon’s invocation is to conquer nature through action, and so the focus of the technologic schema has been on systems of the first type—systems of the second or third types are normally ignored or approximated by a model of the first type. The predictive control this methodology potentially allows has for centuries far outweighed the doubts raised by

“exceptional cases” that could not be made linear. It was always thought that better linear models would more and more closely approximate reality, until no more “exceptional cases” were left. We shall see in the next section that this is not at all what happened.

First, let us draw the discussion back to descriptive schema. Attractors are one of the principle tools of the technologic descriptive schema. In technological realms, stable equilibrium attractors are the focus, because technology is most useful when it is predictable. It is in these technological realms that most people encounter science, and in many ways, technology is what people—including scientists—believe science is about. This is why I call the modern descriptive schema technologic. For even outside the realm of engineering, people view worldly artifacts in terms of their utility—they break complex systems into parts for the purpose of conquering in action. This is the problem—for linear science is not the only sort of science there is; it is merely the only type with which most people are at all familiar. The assumption made on this basis is that linear methods are appropriate in all cases, that the reductive method always works, and that this always results in the ability of humans to control their environment. In the next section, we will investigate problems in all three of these conclusions.

Section 4: Problems with Linearity and Reduction

In the existing sciences much of the emphasis over the past century or so has been on breaking systems down to find their underlying parts, then trying to analyze these parts in as much detail as possible. And particularly in physics this approach has been sufficiently successful that the basic components of everyday systems are by now completely known. But just how these components act together to produce even some of the most obvious features of the overall behavior we see has in the past remained an almost complete mystery.

—Wolfram NKS 3

The tendency in an object-oriented schema is to assume that a collection of simple objects will inevitably interact in a simple way—that from order comes more order. The corollary of this is the assumption that complex behavior must arise from the interaction of complex elements. The following section examines several commonplace systems in which these assumptions fail to hold true.

Linear science is very good for describing or predicting some systems—for example, planetary motion and projectile motion, and simple mechanical systems (springs, pendulums, rolling balls, and so on). Nevertheless, linear science is simply terrible at other jobs, such as predicting the weather. This is because, quite simply, weather is a nonlinear system. The basic premise of linearity is that a small change in initial conditions will result in a small (linearly predictable) change in results. If a cannon fires two shells with nearly identical weight, angle of inclination, and charge, the two shells will land at almost the same spot.

But if I have a weather system that I start up with a certain temperature and a certain wind speed and a certain humidity--and then I repeat it with almost the same temperature, wind, and humidity--the second system will not behave almost the same. It'll wander off and rapidly will become very different from the first. Thunderstorms instead of sunshine. That's nonlinear dynamics. They are sensitive to initial conditions: tiny differences become amplified.

—Crichton 75-76

That is the key: the technologic version of reduction is linear, which means that parts are purely additive. A complex linear system can be broken into simpler pieces, the pieces analyzed, and then the results of each part added together to get exactly the same result as if the whole system had been analyzed. That is, the whole is *exactly* the sum of the parts. But “it does not say in the Bible that all laws of nature are expressible linearly” (Fermi in Gleick 68). Indeed, “to call the study of chaos²¹ ‘nonlinear science’ is like calling zoology ‘the study of non-elephant animals’” (Ulam in Gleick 68).

The technologic schema is incapable of accurately describing nonlinear systems because its language is linear. We normally do not worry about this because the perseverance effect has fooled us into thinking that nonlinearity is the exception rather than the rule. In those cases when we must discuss nonlinear systems, we attempt to force it into a linear model. As we become familiar with it, we come to think of the linearized model as representing the real system instead of a limiting case of it. In fact, however, it is just that the technologic schema knows how to talk about linear systems and not about nonlinear ones. After all, “if you could write down the solution to a differential equation, then necessarily it’s not chaotic, because to write it down, you must find regular invariants, things that are conserved, like angular momentum. You find enough of these things, and that lets you write down a solution. But this is exactly the way to eliminate the possibility of chaos” (Yorke in Gleick 68).

It is somewhat shocking to realize just how many everyday things can only be described by nonlinear science, for example, the weather (mentioned above) and dendritic crystal growth (in, for example, snowflakes). In nonlinear systems, reduction fails to account for collective behavior (e.g. flocking birds) and the parameterizable

²¹ By ‘chaos,’ Ulam means any and all fields of study impacted by the results of nonlinear science—or, as he would have it, any and all fields, period.

behavior of the discrete logistic equation (used, e.g. to describe population growth). Perhaps the most obvious case of complex behavior is life; biological systems are astoundingly complex, the process of evolution is critically dependent on both initial conditions (e.g. DNA) and environmental conditions, and evolution has a three billion year head start on the theories that discuss it. We shall outline examples of each of these systems and then draw the discussion back to descriptive schema once more.

Subsection i: Nonlinear systems: Snowflakes and Dissipative Systems

Linear science normally insists that a small change in initial conditions will result in a small change in results. It is often claimed that no two snowflakes are identical. Surely, snowflakes form in nearly identical initial conditions. How is it, then, that these two statements can be true? Simply put, snowflake formation is non-linear. Snowflakes are dissipative structures; the rate of growth of the dendritic crystalline structure is limited by the rate of heat dissipation through the outer boundary. Heat diffusion creates instability, while surface tension creates stability. The natural molecular symmetry of H₂O yields a built in preference for six-sided crystal formation at microscopic scales. The balance of stability and instability in the dissipative structure amplifies this molecular-scale preference into the six-sided snowflake with which we are all familiar. The direction of crystal growth at a given instant is critically dependent on the exact temperature, humidity, and molecules surrounding the snowflake as it falls through the turbulent atmosphere (Gleick 309).

In reality, linear systems are the exception—the systems of technology are specifically chosen to be predictable and specially constrained to linear behavior. Nonlinear systems with complex interactions such as those of dendritic crystal growth are the rule. Just as the global structure of a snowflake **emerges** from the details of the collective behavior of a large collection of water molecules, so structures emerge from many nonlinear systems. Yet, not all of them involve the immense complexity seen in snowflake formation. Indeed, the next two subsections explore the emergence of complex behavior from relatively simple rules.

Subsection ii: Emergent behavior in BOIDs: Complexity from Simple Rules

BOIDs are simulated birds. They are simple computer programs living in a simulated two-dimensional environment with other BOIDs and various obstacles. BOIDs have incredibly simple rules, taking the form:

- 1.) Stay close to other BOIDs.
- 2.) Avoid running into things.

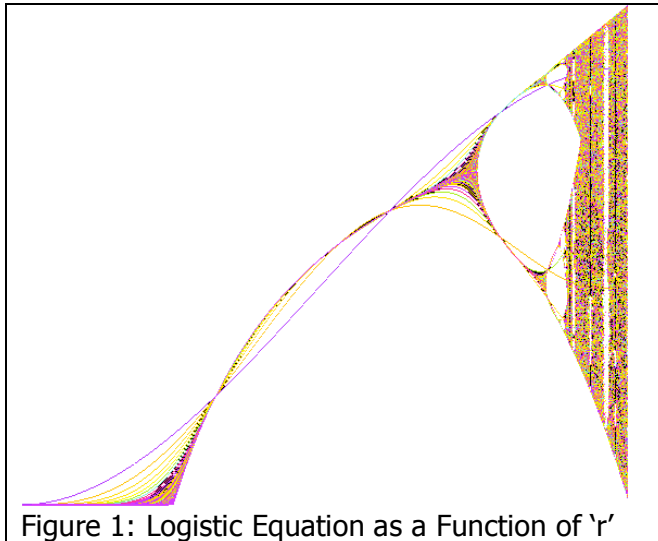
From these two rules emerge the complex flocking behavior with which we are all familiar: the entire flock of BOIDs will turn together, avoiding obstacles by splitting to go around it, rejoining on the other side, moving in what appears to be highly choreographed association that would seem to require a high degree of sophistication, communication, and central command. Yet, if BOIDs accurately depict what occurs with actual birds, this sophistication is emergent—it is a result of the interactions of a large number of essentially simple creatures, each following incredibly simple rules. From simplicity, complex behavior can arise (Stacey 73). The complex behavior arises because of the interaction of simple components.

This emergent behavior is essentially unavailable to the technologic schema, because the basic methodology of reduction is to break a complex system into its parts under the assumption that collective behavior is nothing more than the sum of the behaviors of the parts. In some sense, of course, this is true. However, what is usually missed is that complex collective behavior does not imply complex individual rules. BOID rules are simple, yet complex behavior emerges in collections of BOIDs. Of course, it does not follow from this result that new behaviors emerge from all possible collections of individuals; the point is merely that some properties of collections are not

reducible to properties of individuals. Of the sorts of systems for which this is true, more later.

Subsection iii: Parameterizable Population Behaviors in the Logistic Equation

Population biologists use the equation $x_{N+1} = rx_N(1 - x_N)$ to describe the growth of certain biological systems as a function of the parameter r , the reproductive rate of the population. Figure 1 shows the behavior of this logistic equation as a function of r . At



low values of r , the population dies off. At middle values of r , the population grows to some fixed final value. But when r grows above 3, two solutions exist for the final population value—essentially, the population will fluctuate between these two values. As r grows still larger, the lines split repeatedly.

These bifurcations remained stable for quite some time, so that a population would follow a repetitive n -year cycle, where n was twice the number of bifurcations the plot had experienced. The bifurcations came as r increased by smaller and smaller amounts, so that infinitesimal changes in r resulted in large differences in the number of bifurcations. At a critical point, the system breaks down and populations behave chaotically.

In such a situation, the lessons of linear systems are useless in trying to control or predict the behavior of the system—even a system as simple as the logistic equation, which has *only one parameter*. The ubiquity of nonlinear systems and resulting emergent behaviors heavily militates against the ability of humans to live up to the Baconian dictum of control.

Subsection iv: Evolution and Three Kinds of Randomness

Much work has been done in the past several decades in attempting to construct plausible stories about how evolution can account for two facts about biology: (1) the same basic large-scale features, such as eyeballs and livers, show up over and over, and yet (2) the sexual recombination of DNA, in conjunction with random mutations, is supposed to provide the mechanism for large-scale change (e.g. speciation). It seems unlikely, for example, that eyeballs are the only large-scale structure that can provide the function that eyes do. This subsection discusses two mechanisms that go a long way toward clearing up this apparent paradox for evolution: randomness and lock-in.

Informally, “**random**” describes any relationship without an obvious pattern. As a result, randomness itself defies immediate description, especially in non-subjective terms. However, it seems that randomness relates to the predictability of a system. That is, a predictable system is not random, while an unpredictable system is random. One simple way to define randomness is to substitute the notion of indeterminacy for unpredictability in the previous statements. In such a view, no deterministic system can rightly be considered random, for the rule-driven determination of the present state from the previous one precludes any real indeterminacy—all there can be is *apparent* indeterminacy due to incomplete knowledge of the (deterministic) system. That is, practical limitations such as lack of knowledge or computational power are the cause of the illusion of unpredictability. For those theorists who also believe that the laws of nature are completely deterministic, then, randomness is a useless term, except in the case of undecidable systems.²²

²² Recall that the halting problem (Page 16) suggests that there are general questions about systems that are *in principle* unanswerable (and therefore unpredictable) because of their undecidability.

The problem with this approach to randomness is that it rather poorly reflects the common sense notion of the word. It may therefore be more appropriate to speak of randomness as an epistemological property rather than one of physical reality. Still, as is usually the case in science, definitions are meant to agree with common sense notions, yet not refer to subjective aspects of a phenomenon.

One systematic definition of randomness relies on information content (i.e. the amount of information required to encode the state of a given process). The problem with this approach is that relatively simple descriptions (for example, the program description of the Rule 30 cellular automaton shown in Figure 5 on page 48) can describe what both statistical methods and common sense description would call random. In particular, there appears to be no shorter way to discover the color of the cell in the center column of the n^{th} iteration of the Rule 30 cellular automaton than to run the program for n iterations. No statistical regularities have been found in Rule 30. When expressed as a decimal number, it never repeats. And it is certainly the case that the human eye detects no pattern in those black and white squares. Yet a complete program specification for Rule 30 can be given in one sentence: make the color of the cell the reverse of its left neighbor unless the cell and its right neighbor are both white, in which case make the color of the cell the same as that of the left neighbor.²³

One possible explanation for this is that such systems appear to us to be random because of some peculiarity of human mental processes. It is possible to imagine a Martian whose mind easily grasps the simplicity of the Rule 30 cellular automaton, yet misses the simplicity of, say, a checkerboard pattern.

²³ See Part III for more information about cellular automaton rules.

In Part III we will see another alternative, one that supports the common-sense notion that randomness is linked to predictability. Universal systems (such as the Rule 110 Cellular Automaton) can seem random because they are computationally equivalent to all other universal systems (including, say, brains).

In any case, humans generally mean their common sense notion of randomness when they say a system is random. For the moment, we will use this fact to sidestep the hard work of properly defining randomness generally. Instead, the remainder of this discussion focuses on three types of randomness: randomness from initial conditions, randomness from the environment, and intrinsic generation of randomness. The first two types of randomness are the most familiar to people who are familiar with the technologic schema.

In some systems, random initial conditions never settle down to steady outputs, although the behavior may still be determinate (in that the system will always behave in exactly the same way given exactly the same inputs). One simple example of this is a computer memory system: assuming it is operating properly, the memory system does not change the input at all, so any randomness in the output is simply a reflection of randomness in the input. Of course, systems cover a vast spectrum from those whose output is critically dependent on initial conditions to those that settle on some determinate state regardless of input. But even without random initial conditions, some systems can behave randomly.

Most people are relatively familiar with a multitude of technological systems, such as toasters, television sets, and automobiles. Engineers normally design these pieces of technology to be predictable—so that they operate in essentially the same manner at every use. In such systems, any randomness at all is usually assigned to some external

source, as when a boat tilts based on the complex pattern of waves passing beneath it. Yet, even this sort of randomness does not complete all possibilities. For there are some systems that we call random even though their initial conditions are nonrandom and the system is not perturbed by surrounding systems.

The source of this third brand of randomness is not so familiar. This is the intrinsic generation of randomness. Certain important pieces of technology depend on just such intrinsic generation of unpredictable behaviors. For example, electric circuits that serve as pseudo-random number generators sometimes operate by amplifying the very small-scale motions of atoms within a crystalline lattice. These motions are random in the common-sense way even while they are determinate. While talking within the bounds of the technologic schema, it is quite easy to miss this sort of randomness, because the technologic schema is bound up in the idea of the design and purpose of systems. However, design is the wrong framework to use when discussing a natural process such as evolution.

Many of the people who find the evolution of large-scale structures such as eyes so unbelievable do so because they are unable to escape the notion of purpose in their view of evolution. For example, a common creationist objection to the Darwinian theory of evolution is that it cannot explain how half an eye is useful to a creature, and so eyes must have been designed all in one step. Eyes are, in other words, irreducibly complex. But this objection essentially begs the question of design. A better crucible for determining whether half an eye might ever have evolved naturally (or deterministically) is to ask whether a creature with "half an eye" (say, a creature with a photosensitive patch of skin) has an advantage over a creature with no eye at all. The answer now seems clearly to be 'yes.' A creature with a photosensitive patch of skin might be better

apt to avoid predators by avoiding their shadows, and therefore be more likely to pass along its genes, including those specifying the photosensitive patch of skin. As long as each mutation proffers some advantage to an individual (or, at least, offers no significant disadvantage), the likelihood that the mutation will spread through the species is high. The mutation will, essentially ***lock in***.

“Lock-in” is a term from economics that reflects the tendency of a competitive market to favor early solutions over late (Waldrop 34-42). For example, the VHS cassette format was firmly locked into the market on video recording media when Beta (which was generally agreed to be slightly superior to VHS in its technical capacities) was introduced. Beta did not take over, however, because VHS had locked into the infrastructures supporting the format: for example, many consumers already owned VCRs. Even though VHS may not have been the optimal solution to the problem of video recording, it hit the market first, and its proliferation was great enough to dominate the industry for several decades before a new medium, DVD, was able to edge into the market.

The translation from economics to biology is not immediate, of course. It is clear that the survival of a product is analogous to the survival of a trait, but where does the ‘infrastructure’ come into play? While the economic market moves relatively quickly, so that VHS and Beta were introduced only a few years apart, the biological market (so to speak) moves quite slowly. Moreover, people design products, while traits evolve. Even with these translation difficulties, lock-in is still helpful to a discussion of evolution.

For example, it might have taken millions of years for nature to evolve eyeballs from photosensitive cells. In biology, then, the ‘infrastructure’ is just the millions of years of development necessary to write the genetic code to specify a trait like an

eyeball. Even if photosensitive cells could evolve into some completely different sight mechanism that would proffer a greater advantage than do eyeballs, such a trait is unlikely to evolve merely because, by themselves, photosensitive cells proffer little or no advantage to a creature that already has eyes. Furthermore, the allocation of resources to this new trait would probably leave some other trait at a disadvantage. It is in this way that large-scale features such as eyeballs and livers can lock-in early in the evolutionary tree.

Putting the concepts of randomness and lock-in together in this way is suggestive. It seems plausible that evolutionary theory might one day adequately explain the seeming paradox of the proliferation of large-scale features despite random mutation. For the present, however, it is important to note that, from within the technologic schema, it is not at all obvious how to even describe such systems as evolution.

Subsection iv: Implications for the Technologic Schema

The more we study the major [social and ecological] problems of our time, the more we come to realize that they cannot be understood in isolation. They are systemic problems, which means that they are interconnected and interdependent.... Ultimately, these problems must be seen as just different facets of one single crisis, which is largely a crisis of perception. It derives from the fact that most of us... subscribe to an outdated worldview, a perception of reality inadequate for dealing with our... interconnected world.

—Capra 3-4

For the past several decades, the psychological tendency to believe our schema long after ample information has shown it to be inadequate to the task of description has become more and more heavily outweighed by the increasing failures of the technologic schema. We have reached something of a crisis of schema, where the most successful aspects now appear to be the most virulent, the most problematic.

The major problem with the technologic schema is not that it predisposes people to believe that they ought to *try* to control their environment, but that it predisposes people to believe that it is *possible* to do so in the first place. What we have just seen is that, in science, static or periodic patterns arise only in simple linear systems. These are the systems that technology exploits. For the most part, we are at a loss at what to do in more complex systems, for example systems with feedback, where every component affects every other component. But this is certainly no excuse for ignoring such systems. Perhaps the most obvious example of this is in ecological systems—the complex interactions of various creatures within an ecosystem are sometimes describable quantitatively, but can rarely be simplified into predictable linear equations. It is obvious that we need to deal with ecosystems, but the technologic schema affords no such method. The next part offers one answer to the question of how we can generalize our descriptive schema to force ourselves to consider emergent behavior

without losing all of the progress we have made in science and in culture over the past two millennia.

Part III: Interaction: a New Descriptive Schema Emerges

At the end of Part II, we discovered that the central problem with reduction is that, because it focuses on the properties of individual objects, it misses the collective behaviors that emerge from the interaction of multiple entities.

From the tradition of the existing sciences one might expect that [the nature of collective behavior] would depend on all sorts of details, and be quite different for different types of physical, biological and other systems. But in the world of simple programs... the same basic forms of behavior occur over and over again almost independent of underlying details. And what this suggests is that there are quite universal principles that determine overall behavior and that can be expected to apply not only to simple programs but also to systems throughout the natural world and elsewhere.

—Wolfram NKS 4

Recently, these collective behaviors have become important enough that we have begun to abandon the technologic descriptive schema and are now searching for a new shorthand²⁴—a new descriptive schema with which it is not just possible but necessary to discuss collective behaviors. Through the discussion of the problems of the technologic schema, we have seen many of the features the new schema will likely have, yet we cannot predict exactly what form the new schema might take if allowed to emerge on its own. We could simply wait and see, but we have seen that the ontological implications of a descriptive schema have far-ranging implications for the entire body of knowledge the schema helps to interpret. For this reason, we will create a new descriptive schema from scratch, so that we know just what implications it has.²⁵

This new schema is based on interactions between entities (and the emergent properties thereof) instead of the properties of the individual entities that compose

²⁴ This is probably why such terms as “butterfly effect” have entered our common vocabulary. It may also explain the popularity of such works of fiction as Jurassic Park.

²⁵ It is perhaps likely that an artificial descriptive schema will be about as popular as an artificial language (such as Esperanto), but I hold out some hope that this work may influence in some small way the formation of a real descriptive schema.

these interactions. We will begin by investigating one of the simplest abstractions of interaction, the cellular automaton. We will see that cellular automaton rules fall into four classes, and we will investigate the properties of each of these classes. Finally, we will generalize these results, showing that they can apply to other systems. Only after this groundwork will we be able to explore the implications of such a system for human understanding of the world. We shall withhold discussion of this last issue until Part IV.

Section 1: Cellular Automata

Cellular automata are discrete cells whose state is *automatically and completely* determined by their previous state and the states of neighboring cells. That is, cellular automata systems evolve independently of external input. At the suggestion of Stanislaw Ulam,

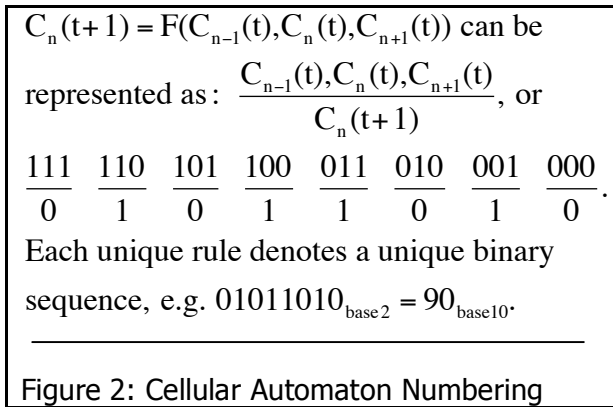
John von Neumann, the brilliant Hungarian mathematician, invented cellular automata in the 1950s, during his quest for self-reproducing machines. Cellular automata...are a kind of complex dynamical system. Imagine an infinitely large grid of squares.... Each of the squares, or cells, may be either black or white, depending on the activity of the neighboring cells. Simple rules govern the state of each cell, such as, if four or more of a cell's contiguous eight cells are white, then the central cell changes state... Cellular automata progress through a series of states, at which each cell examines the activity of its neighbors, and reacts according to its rules.

—Lewin 46

Cellular automata are discrete, deterministic cells whose future state is dependent on the present state of nearby cells. Each cell is essentially a finite state machine (where some number of inputs, together with the present state of the machine, determine the state transitions), but this misses the point: the important behavior of cellular automata is not the actions of individual cells, but the collective behavior of some group of cells. In the early 1980s, Stephen Wolfram began investigating the properties of an even simpler variation of cellular automaton—the simplest possible, in fact.

Wolfram's cellular automata are composed of a single row of binary automata, so that the state transition of cell C_n is governed by the current state of C_n and two neighbors (C_{n-1} and C_{n+1}) and the two possible resultant states (black or white, in following pictorial representations), for a total of just $2^3=8$ states and a total of just $2^8=256$ possible sets of transition rules. Formally, $C_n(t+1)=F(C_{n-1}(t), C_n(t), C_{n+1}(t))$. The

function F can be represented as a logical combination, an arithmetic operation (modulo 2), or exhaustively, as shown in Figure 2 (below). The decimal equivalent of this exhaustive definition completely specifies the particular cellular automaton, so that the rule represented in Figure 2 is Rule 90. Again, there are only 256 such rules, and this is a number small enough for exhaustive analysis.



Like Stanislaw Ulam decades before, Wolfram's great insight in the early eighties was not, trivially, that computers can do computation, or, trivially, that deterministic physical processes evolve in a manner very

similar to computation. His insight was simply that doing computations on computers to simulate physical processes, rather than using standard methods of finding equations, could lead to new or useful results—and that it was therefore a worthwhile endeavor.

Lorenz's earlier experiments with a linked three-equation discrete-time weather simulation (in which arbitrarily sensitive dependence on initial conditions led to vastly unpredictable results and spawned the science of chaos) led most scientists to believe that this sort of discrete-time approximation was useless for practical science—precisely because, though repeatable, the results could not be predicted without arduous and costly computations (except very generally, with ideas such as attractors. Lorenz's equations, for example, led to a rather beautiful three-dimensional attractor in the shape of a butterfly [Gleick 28]). But Wolfram came to the opposite conclusion: discrete simulation leads to a greater reflection of reality; that is, that the immense complexity in the results of these calculations was a reflection of complexity in the system being

simulated, and *not* just an artifact of approximation. Instead, Wolfram concluded, it was the endless linearization performed by scientists in the process of creating equations in continuous mathematics (in particular, differential equations) that introduced *simplicity* that was not present in reality (Malone). This brilliant leap came along with his classification of cellular automaton systems into four categories.

Section 2: Four Classes

Class I rules necessarily resolve themselves into some definite state after only a few state evolutions, and remain at this uniform final state for all future time (see Figure 3.

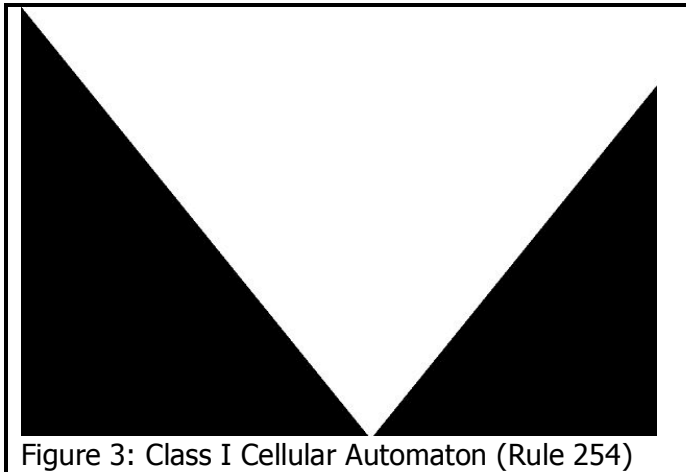


Figure 3: Class I Cellular Automaton (Rule 254)

It should be noted that the system is evolving from an initial condition of a single white cell in the bottom row. Subsequent time steps are represented as subsequent rows going up the picture). Class I systems are absolutely

predictable—trivially so. No matter what the initial conditions, as time approaches infinity, the system takes on a known, static state. Because of the locality of cellular automata, no result can spread faster than one cell per time step in each direction.

Class II rules have many possible final states, but each of them is composed of—at most—repetitive or nested structures (see Figure 4, which shows the right half of the

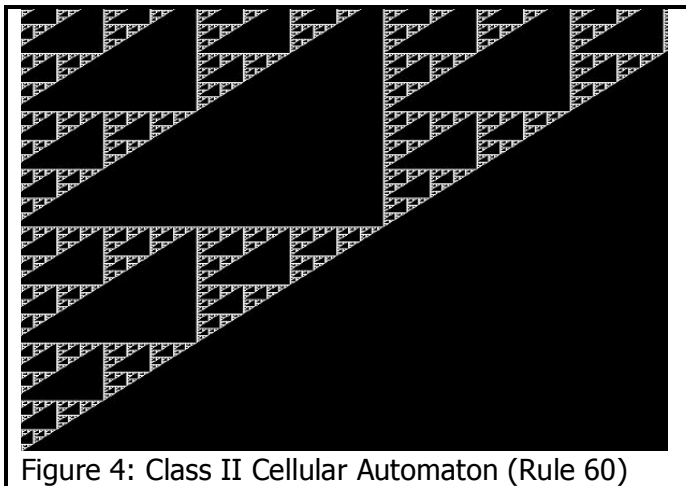


Figure 4: Class II Cellular Automaton (Rule 60)

symmetric pattern of growth). Class II systems are predictable, and are analogous to closed-form mathematical expressions such as differential equations. Such systems, in fact, are the usual domain of linear science. The

state of cell $C_n(t)$ is dependent on the initial conditions for cells in the range $\{C_{n-r} \dots C_{n+r}\}$, where r (the range) is fixed for all time. Thus, any change in initial conditions affects the outcome of cells no further than r away.

Class III rules are effectively random: no long-term structures are apparently possible. In Figure 5, a certain amount of order exists in diagonal structures, but (for example) no one has been able to discover *any* regularity in the center column. Wolfram, in fact, owns a patent on a hardware pseudorandom number generator

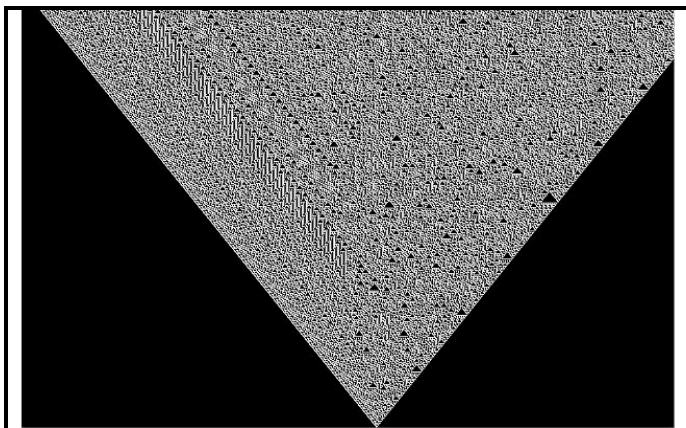


Figure 5: Class III Cellular Automaton (Rule 30)

composed of a bounded Rule 30 cellular automaton, and his *Mathematica* program uses the Rule 30 algorithm for its randomization functions. What qualitatively differentiates Class III rules from Class I or II is that

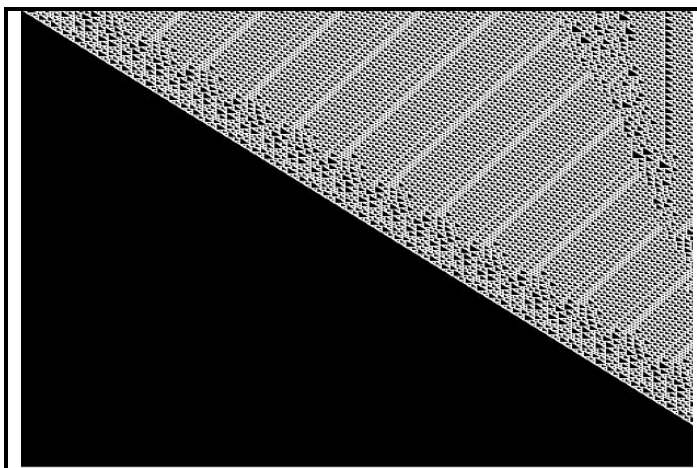


Figure 6: Class IV Cellular Automaton (Rule 110)

there is apparently no way to predict the state of cell C_n at time step t without actually running the automaton system for t steps. Quantitatively, what distinguishes Class III

systems is that cell $C_n(t)$ depends on the initial conditions of cells in the range $\{C_{n-t} \dots C_{n+t}\}$, where t is the time step. That is, as time increases, cell C_n encodes information about an increasingly large range of the initial conditions.

Traditional science usually stops at these three classes. However, amongst the 64 fundamentally different two-color nearest neighbor rules²⁶ there is one rule that does not fit any of the first three categories. This is a Class IV rule, in which relatively simple localized structures move about and interact in complex ways (see Figure 6, which shows the left half of the asymmetric growth pattern). Class IV rules differentiate themselves from Class II rules in almost the same way as Class III rules. However, Class IV rules are different from Class III rules in a very important way. The dependencies of cell C_n at time t cannot be described as a constant range of cells $\{C_{n-k} \dots C_{n+k}\}$ or as an expanding range of cells $\{C_{n-k*t} \dots C_{n+k*t}\}$. A requirement for Class IV systems is that "there must always be certain structures that can persist forever in it" (Wolfram NKS 281). These structures have a growing dependence on initial conditions, but because of the complex interactions of these moving structures, it is not possible to predict just how this dependence grows with time. It turns out—at least in the case of cellular automata—that these structures provide the capability of universality, and this means that their behavior as time grows large is undecidable.²⁷

Is it reasonable to treat these systems differently merely because we humans are not capable of recognizing a pattern in their behavior? After all, the evolution of all cellular automata is governed by simple rules. Is there something fundamentally different about some such systems, or is the difference some artifact of human cognition? What, in other words, is the significance of the varying dependence on initial conditions?

²⁶ There are a total of 256 rules, but this number is halved by ignoring left-right symmetrical and halved again by black-white symmetrical cases, leaving 64 unique rules.

²⁷ In the sense that there is no shortcut method of predicting their behavior. That is, the only way to determine the behavior of Class IV cellular automata at time t is to run the program (or an equivalent program, which must also be universal) until time t .

It would be easy to sidestep this issue by making the claim that what we are talking about is descriptive schema—and that it is therefore not only appropriate but also requisite that the schema reflect the way humans perceive reality. However, as we have already discussed, our belief in descriptive schema as a true reflection of reality (rather than merely convenient) forces us to take the claims of the schema seriously. It turns out, as we shall see in Section 4, that the feature of universality seen only in Class IV systems is indeed fundamentally different.

Section 3: Qualitative Properties of the Four Classes

With the definition of four classes of behavior for cellular automaton state evolution rules, it is possible to broadly identify the properties of these classes of interaction. “Many features of cellular automata depend only on the class in which they lie and not on the precise details of their evolution” (Wolfram CAC 423). **Table 1** tabulates several of these features.

Table 1: Cellular Automaton Behavior by Class				
	Class I	Class II	Class III	Class IV
General Behavior	Spatially homogenous state.	Simple stable or periodic structures.	Chaotic aperiodic structures.	Complicated localized structures, some propagating.
Comparison with Continuous Dynamical Systems	Limit points.	Limit cycles.	Strange attractors.	Nonlinear behavior.
Effect of Finite Initial Conditions	Pattern disappears with time.	Pattern evolves to a fixed finite state.	Pattern grows indefinitely at a fixed rate.	Pattern grows and contracts with time.
Effect of Small Changes in Initial Conditions	No change in final state.	Changes in a region of finite size.	Changes over a region of ever-increasing size.	Irregular changes.

—Based on Wolfram CAC 161

Section 4: Generality of Cellular Automaton Results

It is all well and good to talk about the properties of some arcane mathematical system, but our intention is to create a descriptive schema. For this, we need to show that the scope of our results is broad enough to describe a wide variety of real-world systems. We need to be sure that the simplicity of a cellular automaton system does not preclude the application of cellular automaton results to, for example, physical, biological, and social interactions. To turn the perseverance effect to our favor, we need to be sure that there can be an isomorphism between the elements of an automata model and the elements of reality. The next section deals with several of these issues, beginning with universality, discrete versus continuous time and space, and local versus non-local rules.

A model is an abstract representation of a system. There is no *requirement* that there be any direct correspondence between elements of the model and elements of the actual system. However, a model is normally only useful when the elements of the model reflect some fundamental element of the system. "Thus, for example, a traditional mathematical model might say that the motion of a planet is governed by a set of differential equations. However, one does not imagine that this means that the planet itself contains a device that explicitly solves such equations. Rather, the idea is that the equations provide some kind of abstract representation for the physical effects that actually determine the motion of the planet" (Wolfram NKS 365-366). Crane makes careful use of terminology to distinguish between the computation that occurs in Newton's gravitational equations and the physical instantiation of those equations (102). This is a subtle point. The claim is that it is useful to view the universe as an ongoing computation, and finding out what computations nature instantiates is the instrumental

goal of science.²⁸ The question is whether the great success of science at finding such computations is due to the fact that the universe actually resembles such computation or whether three hundred years of the perseverance effect has fooled us all into thinking that this is the case.

Even with the distinction between computation and instantiation, there is the inherent assumption that it is possible to capture the relevant details of the natural world in terms of a function (in the case of Newton) or simple program (in the case of Wolfram). The simplistic view of this is that the instrumental goal of science (to find out what computations nature instantiates) is contingent on the universe being deterministic—that is, that the universe has the same restrictions the cellular automaton models have. For many phenomena, it is "not crucial to use the most accurate possible models for individual components. For among other things there was evidence from nature that in many cases the details of the components did not matter much—so that for example the same complex patterns of flow occur in both air and water" (Wolfram NKS 18). Shortly, we will see why this is so (that is, why the restrictions of cellular automata appear not to limit their modeling capabilities). Still, it is worth noting that in all cases the basic restraint of automatic computation is necessary. That is, computation must be contingent upon the evolution rule of the cell, along with previous states of the cell and its nearest neighbors.

A more straightforward question is just how such a simple system could ever hope to describe the real world. It is not obvious how a system with just two states, discrete time, discrete one-dimensional space, and local rules could possibly correspond to the real world, which appears to us to have very many states and to have four intertwined

²⁸ We will revisit this issue later in this section and again in Part IV.

space-time dimensions that evolve continuously, perhaps at the behest of non-local rules! It all comes down to universality. In any deterministic system—including, we would like to think, our universe—the state evolution of the system should be computable.²⁹ **Universal** systems are those that can compute anything that is computable.

Alan Turing posits the Turing Machine as an idealized, abstract model of a computer,

a machine which is only capable of a finite number of conditions q_1, q_2, \dots, q_R which will be called " m -configurations". The machine is supplied with a "tape"... running through it, and divided into sections (called "squares") each capable of bearing a "symbol". At any moment there is just one square, say the r -th, bearing the symbol $S(r)$ which is "in the machine". We may call this square the "scanned square". The symbol on the scanned square may be called the "scanned symbol". The "scanned symbol" is the only one of which the machine is, so to speak, "directly aware". However, by altering its m -configuration the machine can effectively remember some of the symbols which it has "seen" (scanned) previously. The possible behaviour of the machine at any moment is determined by the m -configuration q_n and the scanned symbol $S(r)$. This pair $q_n, S(r)$ will be called the "configuration": thus the configuration determines the possible behaviour of the machine. In some of the configurations in which the scanned square is blank (i.e. bears no symbol) the machine writes down a new symbol on the scanned square: in other configurations it erases the scanned symbol. The machine may also change the square which is being scanned, but only by shifting it one place to right or left. In addition to any of these operations the m -configuration may be changed.

—Turing 231

In other words, the Turing Machine is a finite state machine whose state evolution is at each step determined by its internal state and a single symbol on the tape. Turing's contention is that any possible computation may be encoded in appropriate

²⁹ And here it is important to distinguish "computable" from "predictable." "Computable" means, essentially, that a result can be reached in finite time, while "predictable" means that a result can be written down *before* the actual system reaches that same point. Predictability, in this sense, requires some reduction in the computation that goes on in a system—some shortcut. But a computable system need not be predictable in this sense. Indeed, we shall see that Class III and IV systems are computable but not computationally reducible, and therefore not predictable in the sense just described.

state evolution rules along with the initial conditions of the tape. But because a Turing Machine is itself a computation, there must be a Universal Turing Machine that, through appropriate “programming” (initial conditions on the tape), could emulate any other possible Turing Machine.

Wolfram has shown that his Rule 110 cellular automaton can emulate a Universal Turing Machine, and is therefore itself a universal computer (NKS 676). Therefore, the reasoning that makes any of the infinitely many possible implementations of Turing Machines essentially equivalent also makes any of the infinitely many possible implementations of cellular automata essentially equivalent. This paper focuses almost exclusively in the realm of cellular automata, rather than the more familiar Turing Machine, mainly because of their expressive visual representation and (in the case of the one-dimensional, two-color cellular automaton with nearest neighbor rules) straightforwardness of rule formation. Yet, the goal of this section is to show that this choice is only a convenience—that the results we have seen can be generalized to all computable systems. Wolfram has shown that Rule 110 is universal, and that means that it is equivalent in computational power to a Universal Turing Machine. Moreover, since a Universal Turing Machine can emulate any possible Turing Machine, it can compute anything that is Turing-computable.

So what does it mean to be Turing-computable?

If a computing machine never writes down more than a finite number of symbols of the first kind [0 or 1] it will be called *circular*. Otherwise it is said to be *circle-free*.... A sequence is said to be computable if it can be computed by a circle-free machine. A number is computable if it differs by an integer from the number computed by a circle-free machine.

—Turing 233

That is, a number is computable if it differs by an integer from the number computed by a computing machine that is capable of writing down an infinite number of 0s or 1s. This is because any number—or sequence of numbers—can be represented by some sequence of 0s and 1s. This result is now obvious from the ubiquitous use of binary computers to represent numbers, letters, words, and so forth. For Turing, all it means for a number to be computable is for it to be possible to write that number down using a Turing Machine. The restrictions on a Turing Machine are that it have a finite number of states, that it be closed to external input (other than what is set up as an initial condition on the tape), and that state evolution be completely determined by its present configuration.

The result that Rule 110 is universal, then, simply means that given appropriate initial conditions, the simple rules of state evolution given completely as

$$\begin{array}{cccccccc} 111 & 110 & 101 & 100 & 011 & 010 & 001 & 000 \\ \hline 0 & 1 & 1 & 0 & 1 & 1 & 1 & 0 \end{array}$$

are sufficient to compute *any* number that is computable. What this means is that this incredibly simple machine is capable of as much sophistication as *any other computer*. Of course, there will be practical differences in run-time, ease of programming, and so forth, but the important result is that the simplest interactive system we could possibly devise is capable of the most complex computation possible.

This result is what Wolfram calls **computational equivalence**: "no system can ever carry out explicit computations that are more sophisticated than those carried out by systems like cellular automata and Turing machines" (Wolfram NKS 720). However, there remains the question of whether it is reasonable to say that natural systems can be represented by computations of the kind about which we have been speaking. For example, there is no mechanism within a planet that explicitly carries out a computation

to determine its motion, so applying the principle of computational equivalence to such a natural system is, in effect, implying that the motion of the planet *is* an explicit carrying out of said computation. Wolfram, for example, makes the claim that all processes that follow definite rules can be viewed as computations (716). Although the epistemological limitations such as those discussed in Part I prevent any direct knowledge of such computations, we will stipulate computational equivalence for natural systems;³⁰ even so, there are other features inherent to Turing Machines and cellular automata which may not inhere in real systems. For example, a key feature of Turing Machines is that they have a finite number of states, and they evolve in finite time steps. Although there is at least some reason to expect that the universe does as well, it is certainly possible that it does not.

Linear science is the science of continuously varying quantities. In fluid dynamics, for example, it is well known that the system comprises discrete elements such as molecules of air or grains of sand. But since the equations describe the average behavior of a large number of such particles interacting essentially randomly, discreteness averages out and continuity emerges (Wolfram NKS 329). In a similar manner, discreteness can emerge from continuity. For example, water has qualitatively different behavior at infinitesimally varying (continuous) temperatures near its boiling point—it goes from cohesive fluid to non-cohesive gas (Wolfram NKS 337). In principle, then, continuous and discrete behaviors are independent of whether the system comprises continuous or discrete variables.³¹ Presumably, this is true in both time and space.

³⁰ Just as the animist schema assumes all things have spirits, and the technologic schema assumes linearity, the interaction schema assumes all things are computations.

³¹ This observation also forms the basis for the fundamental theorem of calculus.

The difference in dimensionality is another rather easy problem to resolve: rather than model natural systems with one spatial and one time dimension, we can easily construct an automaton system with, for example, three spatial and one time dimension, or any other number of dimensions we wish. Nearest neighbor rules in the three-space example might involve cubic cells that depend on as few as the six neighbors that share a face or as many as the twenty-six that surround it.

However, perhaps the most important limitation of cellular automata is the locality of their rules. It might be that natural systems are not limited to local rules. Quantum entangled states, for example, may imply non-local rules.³² The quantitative differentiations we have made between the four classes of cellular automata are based on the scope of influence of initial conditions. But in a non-local system, these distinctions seem not to be sensible. If a non-local system is deterministic, a universal system should still be able to simulate it. However, the elements of such a system need not correspond to the elements of reality. To be clear, it should be possible to create *some* automatic system whose elements are isomorphic with the elements of reality. However, there is no need to provide that system if we can show that *an* interpretation

³² The Einstein-Podolsky-Rosen thought experiment demonstrates that quantum mechanics is incomplete under the condition of locality. In the confirming experiment, a particle of zero spin is decomposed into a pair of particles A and B, each with spin ± 1 . Since spin is a conserved quantity, it is known that these two particles have opposite spin, though quantum formalism leaves these spins indeterminate until measured. The two particles travel in opposite directions in space until they encounter spin analyzers. Upon the measurement of particle A, the spin of particle B is known to be precisely opposite that of A, and measurement of B confirms this. If the two particles had an actual spin prior to measurement, then quantum mechanics is incomplete because there is not a complete correspondence between theory and reality. On the other hand, if quantum mechanics is complete, and the two particles truly had indeterminate spin prior to measurement, this would imply the instantaneous transmission of information (the spin) from particle A to particle B. This would be a non-local phenomenon. So far, it is unknown which of these interpretations is right, and so it is an open question whether reality is local (Earman in Glymour 252-255).

of *a* universal system (in particular, simple cellular automata systems) can be made isomorphic with reality.

One resolution to the problem of non-locality lies in the moving structures of the Class IV cellular automata. A "moving structure" is a distinct sequence of cell states that repeatedly shifts a fixed number of spaces to one side over a fixed number of time evolutions unless or until it runs into another moving structure. If each interaction of these structures is interpreted as a single "step" for a non-local system, it is easy to see that the structures can cover long distances between "steps." This solution involves changing our interpretation of what the time variable is, and this causes problems if we are expecting an isomorphism between the system we intend to simulate and the cellular automaton. However, of course, we are *not* expecting an isomorphism between a particular cellular automata and *just any* natural system. Cellular automata are computationally equivalent to other universal automatic systems, so our job is simply to find an interpretation of *a* universal system that *is* isomorphic with the natural system in question. What cellular automata tell us is that all interaction rules fall into four classes, and knowing the class is sufficient to determine quite a lot about the global behavior of the system. It is not immediately obvious what such an automatic system might entail, in part because it is not yet clear that natural systems are non-local.

Part IV: Implications of the New Descriptive Schema

This Part is far more speculative than preceding Parts. I divide it into two sections.

In the first, I examine the structure of the universe using the descriptive schema based on interaction. In the second section, I revisit the ontological implications of the new descriptive schema given the perseverance effect.

Section 1: Four Levels of Interaction

There is a one-way process of increasing feedback, reflexivity, self-organization, and freedom as the world evolves. Elementary particles have polarity but no shape. Atoms, more complex and self-referential than particles, have simple geometric shapes that are symmetrical in many dimensions. With molecules, which could not exist until the universe had cooled enough to permit them, we see the first asymmetrical shapes and the birth of individuality. Molecules have complex feedback systems, many degrees of freedom, and the capacity to organize in periodic structures such as crystals. Living organisms are even more asymmetrical, free, and capable of organization, and they contain a recording of their own structure in the DNA language.

—Turner 337

One-celled organisms evolved into many-celled, highly integrated organisms. Photosynthesis evolved and came to support locomotion--swimming, walking, running, flight. Stimulus-response mechanisms became complex instinctive acts. Warm-blooded animals followed cold-blooded ones. Complex nervous systems, conditioned behavior, and learning emerged. Sentience appeared--sight, hearing, smell, taste, pleasure, pain. Brains coupled with hands. Consciousness and self-consciousness arose. Culture was superposed on nature.

—Rolston 82

In the technologic schema, there was some expectation that psychology would eventually reduce to biology, biology to chemistry, and chemistry to physics. In some sense, this expectation remains. After all, it is not terribly difficult to see how such a reduction might be made. At lower levels, the same basic pattern occurs repeatedly: bits of matter change configurations until some low-energy configuration is found where no alternative configurations may be reached without an injection of energy into the system. For quarks, at the nuclear scale, there are a couple such configurations for the strong nuclear force. Commonly, we call these configurations "protons" and

"neutrons."³³ That is, protons and neutrons are *really* quarks, but these quarks are in a configuration that requires an immense injection of energy to break. This *can* occur, given the right circumstances (say, a collision at near-light speed within a particle accelerator), but under so-called normal circumstances it never happens. Therefore, it is quite reasonable, at the atomic scale, to ignore the fact that each neutron and proton is composed of three quarks and instead model each of them as a discrete particle in its own right. In a sense, we can ignore the strong nuclear force altogether once quarks have found stable configurations as protons and neutrons.

There are two important features that help to characterize the sort of interactions that will occur in a given situation: (1) the scale on which the interactions take place and (2) the difference between the energy of a given matter configuration and the ambient energy. Scale is important because it determines (to a large extent) which forces influence the particles most strongly. The difference between possible configuration energies, E_c , and ambient energy, E_a , is important because it helps to determine the stability of that configuration—that is, its longevity. Let us briefly review the quark→nucleon interactions given above.

The scale is subatomic, so the strongest force is the strong nuclear force. The ambient energy on the surface of the Earth (for example) is very much smaller than the configuration energy of, for example, a proton. This means that it is not possible for the quarks to leave their present configuration. On the other hand, the ambient energy within an active supercollider is high enough that the quarks can leave their bound state and take on virtually any configuration. One way to picture this process is to imagine a

³³ This is of no small significance. The claim is that a proton *is* a certain configuration of quarks. But unlike a reductive claim, which would focus on the analysis of quarks in order to understand protons, the focus here is on the configuration itself. The difference is substantial (although it is by no means a new idea).

particle as a neutrally buoyant ball rolling on a rough landscape representing the energy levels of various configurations. The ball will naturally roll downward, toward some minimum position. In this picture, ambient energy is water. Without water, the ball rolls downward until it reaches a local minimum configuration. But if the ball reaches water before being caught in an energy well, it is quite free to move from one configuration to another below the surface of the water, because the ball is neutrally buoyant.

For the strong nuclear force, there is virtually no place in the universe where ambient energy is high enough for quarks to float freely between configurations; in general, quarks are in bound states requiring a very high energy input to free them. The case is not quite so bleak for their compositions: protons and neutrons are reconfigured with relative ease inside of stars and nuclear reactors. Outside the realm of nuclear reactions, protons and neutrons—along with electrons—find themselves in bound configurations called atoms. This time, however, the force at work is the electromagnetic force—because the strong nuclear force is essentially bound up in the stable configuration of the nucleons.

But where the strong nuclear force has essentially no significance on the scale of atoms, the electromagnetic force has a significant effect on the scale of dozens of atoms. This is because of the separation of protons and electrons in an atom. The separation occurs because electrons cannot overlap, so they have to spread out in a complex arrangement surrounding the nucleus of the atom. These arrangements work best when they are symmetric, and this only occurs with certain numbers of electrons. But the number of electrons drawn to a nucleus is exactly the number of protons residing there. When these numbers do not match up (which is most of the time),

certain super-configurations become possible. A chlorine atom, for example, might swipe an electron from a sodium atom. This gives both atoms symmetric configurations, but it leaves them with charge (+1 and -1), so they stick together as a molecule.

So, if a salt molecule is a configuration of atoms, atoms of electrons and nucleons, and nucleons of quarks, a molecule is just a configuration of quarks and electrons, right? Yes and no. The order of operations is important. If quarks and electrons were put into a jar and allowed to mingle about, it is quite likely that salt would not be the result. A single atom of nickel might arise instead, or twenty-eight atoms of hydrogen, or something else entirely. Quarks have to configure as nucleons before nucleons and electrons can configure as atoms, and nucleons and electrons have to configure as atoms before atoms can configure as a molecule. But what should be clear is that *once* quarks configure as nucleons, it is no great stretch for nucleons and electrons to configure as atoms. In fact, it is useful to consider each stable configuration as a "level" of interaction. So quarks interact on a low level, and the resulting configuration—the nucleon—is a new level of interaction. The nucleon is not simply a collection of quarks; it is a very specific configuration of quarks. In continuing this idea of levels, once nucleons and electrons configure as atoms (a new level), it is no stretch at all for atoms to configure as molecules (still another level).

So it is, too, that molecules have to configure as amino acids before amino acids can configure as deoxyribonucleic acid. Yet, complex as these configurations are, it is no great stretch for them to have arisen quite naturally, building on the complexity that had already arisen.

With this result in mind, it is worthwhile to consider that it may one day be possible to tell a similar story along the way from DNA to simple cellular organisms, and then from one-celled to multi-cellular configurations, or perhaps from single creatures to multiple-creature configurations (say, herds or societies). And once intelligence has arisen in a certain sort of multi-cellular configuration (say, humans), it is possible to imagine yet another level of interaction on the intellectual level (descriptive schemas play a role here). Even if this speculative tale is not correct, it may be that a similar story can be found, and I am confident that this story will involve some of the characteristics featured here (for example, the lock-in of configurations).

My argument is that we can view the whole universe as being composed of interactions of each of the four brands Wolfram describes. Type II, III, and IV interactions are the interesting varieties, and we can understand their difference in terms of order (Type II) and chaos (Type III) or in terms of complexity of the interactions.

Roughly, there are three sorts of entities. First are physical entities, which interact according to the four fundamental forces and which can give rise to biological entities, whose interaction can in turn give rise to social entities (a flock of birds, for example). At each level, interactions of each of the four types occur, but only Type IV interactions, which I term ***dynamically stable***, give rise to stable configurations that can interact at the next level. For example, biological entities are dynamically stable physical interactions. The DNA molecule affords a structure that has remained unchanged for billions of years, yet there has been immense diversity in the creatures the DNA specifies. This balance of structure and flexibility is characteristic of Class IV interactions; in fact, flexibility is impossible in Class I and II interactions and structure is

impossible in Class III. This does not mean that Class I-III interactions do not occur in nature; they occur all the time. However, structures in Classes I and II fall apart with environmental changes, and Class III structures fall apart all by themselves. Biological extinctions, for example, are a result of certain creatures being incapable of adapting to new environmental challenges. So, too, is the death of culture a result of the inability of that culture to adapt to a changing world order. It is often the case that interactions of these types (I-III) are so short-lived that we do not give names to their configurations.

The class to which a system belongs says much about its stability in the face of external influence. A Class I or II system, for example, will appear stable (because it is static). But such systems cannot adjust to significant changes in the environment. In the social realm, the relevant structures are political, economic, and ideological. Focusing on just the political factor for example, a Class I totalitarian state might appear strong, but internal unrest can build until the system breaks apart, for in a Class I structure, there is no outlet for change. In contrast, a more liberal state is able to incorporate changes into its very structure, so that pressure does not build to the breaking point. Such liberal states, I argue, are more dynamically stable than the totalitarian alternatives (all else being equal, of course).

One of the key features to recognize about Class IV interactions is that they can emulate any class of behavior—including Class IV (for example, the Rule 110 cellular automaton could emulate a Universal Turing Machine whose program emulates the Rule 30 cellular automaton). Human society might be considered as a Class IV interaction of humans, who are Class IV interactions of cells, which are Class IV interactions of fundamental particles. Weather, too, may turn out to be a Class IV interaction of fundamental particles. So in one sense, humans and weather are computationally

equivalent—both are universal. But in another sense, they are not equivalent, for the computation weather performs is only one level deep, while the computation human society performs is three levels deep.

Of course, not all natural systems seem to be Class IV interactions of fundamental particles. The moon-earth-sun gravitational system, for example, is a Class II interaction of fundamental particles—one for which the occasional perturbations of comets and asteroids have been fortunately minute.³⁴

³⁴ Though, in point of fact, it is impossible to know, for example, whether a given system is *really* a Class II interaction or if it is a Class IV system emulating a Class II system.

Section 2: A Return to the Ontological Implications of Descriptive Schemas

During our discussion of epistemological limitations of descriptive schemas, we discovered that schemas lend a certain relativity to object formation, and that relativity causes us to choose one of three solutions:

- 1.) We can recognize all possible matter/form combinations and know that “any attempt to state which objects exist is bound to capture only part of the truth” because the list of all possible combinations is infinite.
- 2.) We can choose the eliminativist approach, and claim that only basic elements exist (for example, particles such as quarks and leptons) and all object formation is in our heads—a mere convenience.
- 3.) Or we can choose the relativist approach, and claim instead that the existence of objects is contingent upon (or relative to) some conceptual scheme.

—Adapted from Lynch 63

Though we might have wished to choose, say, the eliminativist approach, we found that the psychological necessity of truly believing descriptive schemas forced us to take the relativist approach instead. This led to the conclusion that the correspondence between schema and reality was extremely important (not merely a convenience). Then we saw that the modern schema, based on linear reduction, had low correspondence with reality, because it overlooks emergence. We created a new descriptive schema in the hopes that it would have a closer correspondence with reality.

This interaction schema implies different ‘levels’ of interaction; the lowest level composed of fundamental particles—perhaps equivalent to the ‘simples’ mentioned in Lynch’s eliminativist solution. Higher levels of interaction are composed of stable configurations of interactants that inhabit lower levels. In a sense, then, we now have the best of both worlds: we accept that the components of the interaction descriptive schema exist relative to our own whim to divide up interactions into the levels we have. Yet we also claim that, at the bottom level these components are real. Furthermore, we

claim that our reason for dividing reality into various objects at other levels in the way we do is not entirely arbitrary; our recognition of dynamically stable interactions guides this choice.

Concluding Remarks

In any epistemological discussion, it would be a mistake to overlook the perseverance effect and its implication that we are naively realist in our interpretation of the world.

In searching for solutions to even the most complex and difficult problems of our day, I feel that the most important tool we have for finding solutions is our ability to look at problems from several perspectives. If a problem seems to evade simple definition, it is perhaps best to abandon the descriptive schema and try to get at the fundamental characteristics of the system.

Though attractors offer the facility for describing many systems, even some complex systems, I have no doubt that future descriptive schemas will also include some facility for understanding emergence and evolution.

The most important lesson of the new schema is that the parts *and* their configuration are crucial to understanding the resulting system.

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* These books contributed to the development of the ideas expressed in this work; although I do not cite them within it, I feel they deserve notice.

Author's Biography

Isaac Record was born in Augusta, Maine on February 12, 1980. He was raised in Windsor, Maine and graduated from Cony High School in 1998. Double-majoring in electrical and computer engineering, Isaac also has a minor in philosophy. He is a member of Eta Kappa Nu and is registered with the State of Maine as an Engineer in Training.